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New large test setup for dynamic testing of soils

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ABSTRACT: At the Soil Mechanics Laboratory, Aalborg University, Denmark a test setup has been developed for tests to determine the behavior of foundations during dynamic loading. The test setup has been developed during the period of February 1992 to May 1994. It has been built to model offshore constructions on sand including ordinary gravity platforms and suction anchors. Furthermore the test setup is suitable for tests of earthquake loaded constructions located on sand. The paper describes the test setup, a newly developed method for reproduction of a saturated sand bed and presents some of the tests carried out since the test setup became operational.

1 INTRODUCTION

The test setup is a part of the center for dynamic measurements located at Aalborg University. The center for dynamic measurements is a cooperation between the laboratories for Structural engineering, Hydraulics and Soil Mechanics at Aalborg University. The test setup described in this paper is developed in the Soil Mechanics laboratory.

The test setup contains an advanced measuring equipment, a load frame and the hydraulic installations, see figure 3.

The criteria for designing the test setup is as follows:

1. To simulate loadings from an earth quake.
2. To simulate loadings from wave forces on an offshore construction.
3. To simulate impact forces.
4. The tests have to be carried out on a saturated sand. The degree of saturation, S_w, must be close to 1.0.

To fulfill the design criteria for the test setup it has to be possible to apply the loads shown in figure 2 to the base. The loads are induced by the three hydraulic cylinders located in the load frame, see figure 1. The flexibility of the test setup allows the cylinders to move in the load frame to make it possible to induce all the loads shown on figure 2 to the base and the steel box when it is located inside the load frame.

2 THE TEST SETUP

The test setup is placed on a separate base to ensure that it does not influence other tests in the laboratory (i.e. consolidation tests and triaxial tests). The test setup is shown in figure 1.

The load frame is made of two steel frames, see figure 3. Each frame has the following dimensions: $l \times b \times h = 4.25 \times 0.45 \times 2.25$ m. The two frames are placed with an internal distance of 1.1 m. The total width of the load frame is 1.55 m.

The test soil is placed in a steel box with the internal dimensions $1.6 \times 1.6 \times 0.65$ m.

To fulfill the general dimensioning criteria listed above, the test setup must be designed according to the following conditions:

A. To simulate an earthquake it is necessary to move the steel box or a base with a frequency up to 30 Hz.

B. To simulate the drainage beneath the base

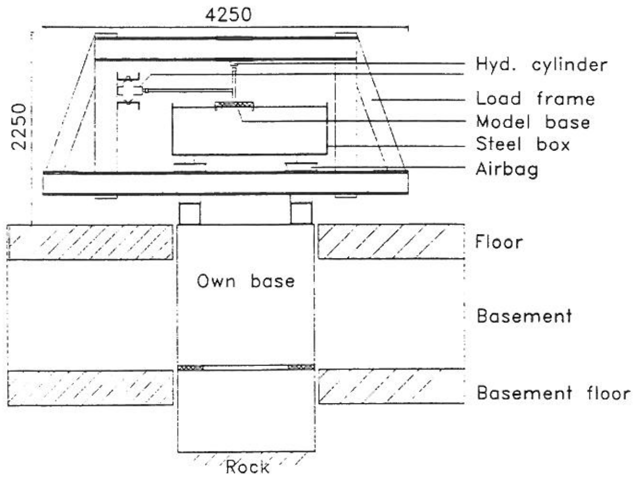

Figure 1: The test setup on the separate base.

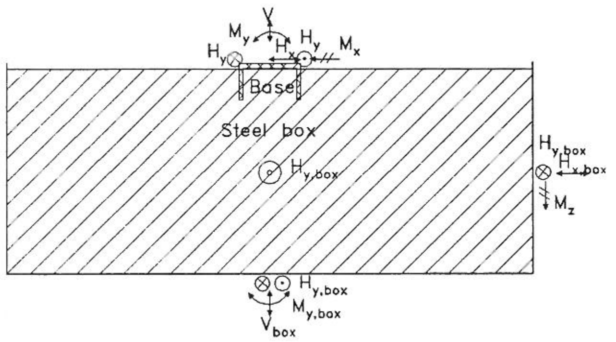

Figure 2: The necessary forces to fulfill the dimensioning criteria for the test setup.

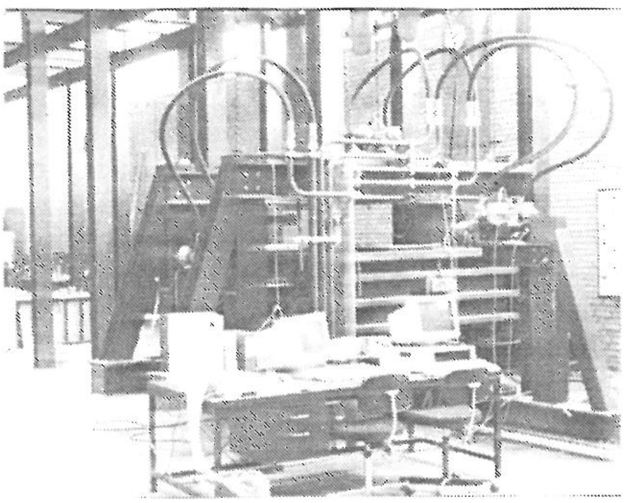

Figure 3 shows the complete test setup.

of an offshore construction or similar structures the base must be as large as possible. A circular base with a diameter of 850 mm. with a base pressure of 175 kPa. is chosen for the first test series. The hydraulic cylinders must induce a force of 100 kN.

C. The simulation of an earthquake will require a maximum displacement of approximately ±25 mm.

Wide flexibility of the cylinders has been achieved by using high pressure rubber tubes at the end of the hydraulic pipes, see figure 3. The rubber tubes ensure adjustment of the position of the cylinders in the load frame.

The steel box is placed on 4 airbags to avoid using one cylinder to lift the box while shaking it. Combined the four airbags can lift approximately 100 kN. The total weight of the steel box with sand is approximately 30 kN.

The four airbags are controlled individually from a valve board, see figure 4.

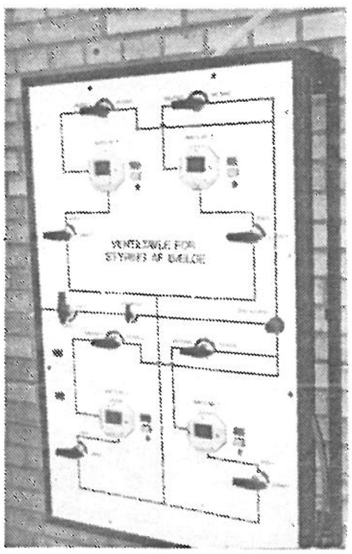

Figure 4: The valve board.

3 THE HYDRAULIC SYSTEM

As described earlier the test setup has been designed to manage different assignments. The requirements for the hydraulic system are listed below:

A. Large force $P = 0$ to 100 kN. Slow frequency, $f = 25\ Hz$, and large displacement, $\delta = \pm 25$ mm.

B. Force $P = 25$ kN. Frequency, $f = 5\ Hz$, and displacement, $\delta = \pm 25$ mm.

C. Earthquake, max. acceleration $\ddot{u} = 0.3g$ and frequency, $f = 30\ Hz$.

To fulfill these requirements the hydraulic system must have an oil flow of $3 \times 127 = 381\ l/min$. The oil flow is produced by a 160 kW. hydraulic pump with an operating pressure of 210 bar. (100 kN) but the pressure can be increased to 300 bar. (150 kN) when loaded statically. Each cylinder has a maximum frequency of approximately 50 Hz.

A recently developed servo control system (PSC) is used to control the hydraulic cylinders. The PSC offers the user a wide range of possibilities. The test setup has to be able to manage a wide range of loading situations, so the PSC is necessary for this test setup.

Two of the three cylinders can be synchronize automatically, the last cylinder has to be synchronized manually. In most cases this is sufficient. If it should be necessary to synchronize three cylinders it is possible to make an adapter for that purpose.

4 THE MEASURING EQUIPMENT

The measuring equipment for the test setup is of a very high standard. The measuring unit is a HBM9012A measuring unit capable of sampling on maximum 12 channels with a maximum sample frequency of 9600 Hz. on three channels and 4800 Hz. on up to 12 channels. The storage capacity is 120000 measurements.

The force is measured by a HBM U9A-force transducer with an accuracy of approximately 0.4 % up to 55 kN. The displacements are measured by HBM W50K or W10TK transducers capable of measuring up to 50 mm. displacements with an accuracy of approximately 0.2 %. The pore pressure is measured by a transducer of the type Druck PDCR81 with a non linearity of less than 0.2 %.

5 REPRODUCTION OF THE SAND BED

As described earlier the sand bed must have a degree of saturation, S_w, close to 1.0. This is difficult to achieve with sand with low permeability, which is necessary if large dynamic loaded structures are to be tested. Two sands have been tested so far. Material parameters for the two sands are shown in figure 5.

Previously in the laboratory a homogeneous sand bed has been successfully achieved by using a method of sand rain which is only possible

Parameter	Silkeborg 000	Baskarp 15
e_{min}	0.67	0.546
e_{max}	0.94	0.858
d_{50}	0.322	0.14
U	1.45	1.78
d_s	2.663	2.644

Figure 5: Material parameters for Silkeborg 000 and Baskarp 15.

with dry sand. In this setup the sand sample is of a magnitude of 1.7 m^3. The method of sand rain cannot be used because it is too time consuming.

During the buildup of the test setup a new method has been developed and tested. The new method is called "The Vibration Method". This method can reproduce a sand bed with saturated sand.

The principle of the method is:

1: Apply an upward water gradient of $0.7 \cdot i_c$ though water pipes in the bottom of the steel box through the sand bed.

2: Vibrate the sand bed with a stick vibrator twice in a certain pattern.

3: Stop the upward water gradient and make the load tests.

4: Loosen the old sand bed by an upward water gradient of $1.0 \cdot i_c$ through the sand and vibrate the whole sand bed in big circles.

5: Start from point 1.

Tests show that the stick vibrator has to be used in a 0.15×0.15 m. pattern, which causes the sand bed to become homogeneous and the time used to reproduce the sand bed is reasonable (approximately 75 minutes).

The stick vibrator is used twice. First the stick vibrator is used to vibrate the complete sand bed.

Test no.	Depth in mm
Test 5	50
Test 6	250
Test 7	500
Test 7b	500

Figure 6: The depths in which the four samples are taken.

Next the surface of the sand bed is vibrated. The homogeneity is investigated by finding the bearing capacity of a Ø100 mm base. The bearing capacity is measured in nine different points on the surface of the sand. The results from these tests show, that it is possible to achieve a very homogeneous sand bed.

Three test series were performed on Silkeborg no.000. In all three test series combined the mean value is calculated to 67.3 kg. with a standard deviation of 3.3 kg. The mean value from each test varies less than ±1 kg. The variation of the mean value is almost identical with the loading step of 2 kg. The loading step is 3 % of the mean value.

The secant friction angle, φ_{pl}, for Silkeborg no.000 is approximately 40°. Such a high friction angle means that the deformation up to failure is very small. When the load exceeds the bearing capacity the failure will occur with large settlements.

Due to the high friction angle and the load step of 2 kg. a deviation of ±1 kg. on the mean value and a standard deviation of less than 5 % of the mean value is considered acceptable.

The vibration method might be problematic due to a possible stratification of the grains down through the sand bed. To investigate the grain size distribution though the sample 4 small samples were taken in different depths, see figure 6.

For each sample the void ratio, e_{insitu}, and the grain size distribution are calculated. The results are shown in figure 7.

Before these tests were performed, three possible options were listed:

1. If the sand bed is completely liquefied during the reproduction the small grains might move to the top of the sample. The biggest grains might not be carried by the upward water gradient.This might cause the biggest grains to fall to the bottom of the sand bed.

2. The sand bed is not completely liquefied during vibration. Small grains might be locked beneath bigger grains.

3. No change.

The grain size analyses show almost no difference between the four curves. There is a slight tendency for the bigger grains to stay in the top of the sand bed. In test no.5 67.6 % of all grains

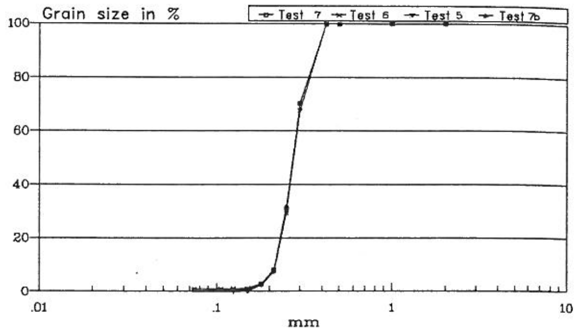

Figure 7: The results of grain size distribution down through the sand bed.

are smaller than 0.3 mm. In test no.7 70.3 % of all grains are smaller than 0.3 mm. Test no.6 shows the same result as test no.7.This indicates that the difference is caused by unreliability of the grain size analyses. Because of these results it is concluded that the vibration method gives a good homogeneous sand sample.

The results found by using Silkeborg no.000 were very good, but the grain size distribution of Silkeborg no.000 is not as fine as a typical sand beneath an offshore construction in the North Sea. For that reason the same tests are carried out on Baskarp no.15. The difference between Silkeborg no.000 and Baskarp no.15 is shown in figure 5. The change of sand does not affect the conclusions made on Silkeborg no.000. The only change is the size of the bearing capacity, the mean value increases from 67.3 kg. to 79.8 kg. and the standard deviation increases to 6.9 kg. or 8.1 % of the mean value.

Small samples have been taken in different places in the sand bed to calculate the degree of saturation. The results of these samples are a void ratio, $e_{insitu} = 0.622$ and a degree of saturation, $S_w = 1.07$. The degree of saturation indicates that it is close to 1.0 and that it is very difficult to take an insitu sample in sand.

Through the tests carried out it is shown that the vibration method provides a homogeneous sand bed. The same reproduction method will be used in future tests.

6 THE FIRST TESTS

The first real test series made in the test setup is shock loading of a Ø850 mm. base. The tests will simulate the Ekofisk storage tank. The Ekofisk

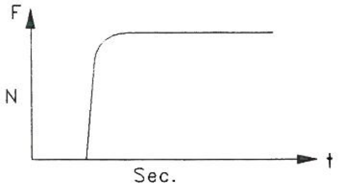

Figure 8: The load history in the shock load test series.

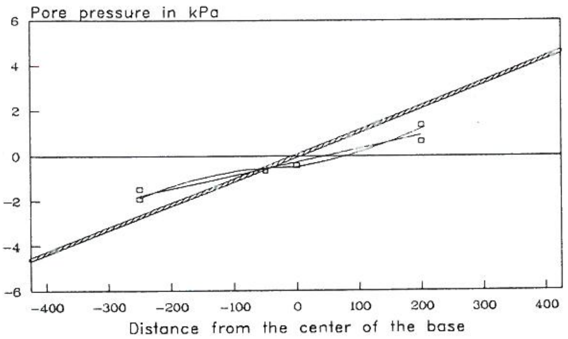

Figure 9: An example of the test results for a shock load.

storage tank is placed in the North Sea on a sand similar to the sand Baskarp no.15. The typical load history for the first test series is shown in figure 8. The horizontal load is applied to the base 250 mm. above the sand bed. Furthermore the base is loaded by a vertical load of approximately 2 times the horizontal.

The test series is performed to investigate the distribution of the maximum pore pressure beneath the base and the drainage with time. This paper concentrates on the distribution of the maximum pore pressure beneath the base.

As the load is applied to the base in the center line of the base, the distribution of pore pressure will be assumed to be a straight line. This is only correct if the theory of elasticity is valid. Figure 9 shows a representative test result. Eleven tests were made in this test series. All tests have the same tendency as the test result shown in figure 9.

The hatched line in figure 9 is the theoretical straight line (TSL). The points are the measured pore pressure. The thin straight line is the best line though all measured points (MSL). The last line will be described later.

The inclination of the MSL is approximately half the inclination of the TSL. This indicates that a straight line is not the right description of the maximum pore pressure.

As shown in figure 9 MSL is lower than zero in the center of the base. This indicates that some dilatation has occurred. Dilatation will not be uniformly distributed over the base. The dilatation will be largest where the pore pressure is largest. When dilatation occurs the sand sample will dilate. This will provide a redistribution of the applied load. Near the edge of the base the inclination of the pore pressure with the distance from the center of the base will be higher than the theoretical line. The inclination is smaller near the center of the base, see the curved line in figure 9 (MCUL). If MCUL is extrapolated to the edge of the base the pore pressure will be higher than the pore pressure found by TSL. A pore pressure higher than TSL is not likely to be measured due to the small drainage time. The drainage time for the base is approximately 0.1 sec. The sample rate in these tests was 300 Hz. The sample rate will provide 30 points to describe the drainage. 30 points is probably not enough points to measure the maximum pore pressure. In future tests this will be investigated further by increasing the sample rate.

7 CONCLUSION

The new test setup makes it possible to carry out large scale dynamic tests on a very homogeneous sand bed. The maximum dynamic force is 3×100 kN. In static conditions it is possible to increase one force to 150 kN. A new method for reproduction of a saturated sand bed is developed. By using "The Vibration Method" a sand bed can be reproduced with the following uncertainties: The mean value of the bearing capacity of a base varies less than 2 % with a standard deviation of 5 %.

The vibration method does not stratify the grains with depths. If the vibration method is used on other materials than Baskarp no.15 or Silkeborg no.000 stratification analyses have to be performed.

8 FUTURE DEVELOPMENTS

At this moment it is not possible to investigate the consequences of a deep water foundation in the test setup, because of the need for water pressure on top of the sand bed. The water pressure system has been designed but has not yet been built.

Presently a large test series is produced in the test setup. This test series is performed to investigate the development of pore pressure beneath a base for different load types, frequency and amplitudes.

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